# Control of Separated Flows and Buffeting in Transonic Flow

**D. Caruana*, A. Mignosi*, M. Corrège#, A. Le Pourhiet#**
*Aerodynamics and Energetics Models Department
#System Control and Flight Dynamic Department
ONERA
2 av. Edouard Belin, 31055 Toulouse, France

daniel.caruana@onecert.fr

## ABSTRACT

*In transonic flow conditions, the shock wave / turbulent boundary layer interaction and flow separations on wing upper surface of a civil aircraft, which induce flow instabilities, "buffet", and then structure vibrations, "buffeting", can greatly influence the aerodynamic behavior. The "buffet" phenomenon appears when the Mach number or the angle of attack of the aircraft increases. This phenomenon limits aircraft flight envelope. The objectives of this study are to cancel or to decrease the aerodynamic instabilities (unsteady separation, shock location movement) due to this type of flow by control systems. The following actuators can be used, "Vortex Generators" situated upstream of the shock location and a new moving part designed by ONERA and situated at the trailing edge of the wing, "Trailing Edge Deflector" or TED. It looks like an adjustable "Divergent Trailing Edge". It is an active actuator, it can take different deflections or be driven by dynamic motions up to 250 Hz. Tests were performed in transonic 2D and 3D flow with models well equipped with unsteady pressure transducers. For high lift coefficients, a selected deflection of the "Trailing Edge Deflector" increases the wing aerodynamic performances and delays the "buffet" onset. Furthermore, in 2D flow "buffet" condition, the "Trailing Edge Deflector", driven by a closed loop active control using the measurements of the unsteady wall static pressures, can greatly reduce the "buffet". In 3D flow "buffeting" conditions, the 2D flow control principle is available but some differences must be considered. Vortex generators have a great impact on the separated flows. The separated flow instabilities are greatly reduced and the buffet is totally controlled even for strong instabilities. The aerodynamic performances of the airfoil are also greatly increased.*

## KEYWORDS

Transonic flow – Control – Closed loop – Separated flow – Buffet – Buffeting – Actuators

## NOMENCLATURE

| | | | |
|---|---|---|---|
| A: | control law gain | ν: | kinematic viscosity |
| alpha, α: | airfoil angle of attack | P(t): | pressure or shock location (control law) |
| c: | airfoil chord length | Q0: | free stream kinetic pressure |
| Cl: | lift coefficient | Re, Re0: | Reynolds number Re=V0 c/ν |
| Cd: | drag coefficient | RMS: | root mean square |
| d, δ, δ(t): | deflector angle | t: | time |
| $\delta_m$: | mean deflector angle | τ: | time delay of the control law |
| δ'(t): | dynamic deflector angle | x/c: | chord-wise position from LE/c |
| M0: | free stream Mach number | V0: | free stream velocity |

*Paper presented at the RTO AVT Specialists' Meeting on "Enhancement of NATO Military Flight Vehicle Performance by Management of Interacting Boundary Layer Transition and Separation", held in Prague, Czech Republic, 4-7 October 2004, and published in RTO-MP-AVT-111.*

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**01 OCT 2004** | 2. REPORT TYPE<br>**N/A** | 3. DATES COVERED<br>**-** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Control of Separated Flows and Buffeting in Transonic Flow** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Aerodynamics and Energetics Models Department ONERA 2 av. Edouard Belin, 31055 Toulouse, France** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES
**See also ADM201868, RTO-MP-AVT-111 Enhancement of NATO Military Flight Vehicle Performance by Management of Interacting Boundary Layer Tranisition and Separation (L'amelioration des performances des vehicules aeriens militaires de l'OTAN par la gestion de l'interaction entre la transition et le decollement de la couche limite)., The original document contains color images.**

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **UU** | **20** | |

# 1. INTRODUCTION

In a general way, the "buffeting" is the structural response to an aerodynamic excitation created by a viscous phenomenon that may exist on different parts of a body in a flow. This aerodynamic excitation, "buffet", is a surface effort due to pressure fluctuations. The following phenomena can produce enough energy to excite the structure:

- pressure fluctuation levels in a flow separation bubble,
- pressure fluctuation levels in a vortex,
- transonic buffet, fluctuations of pressure levels in the shock wave and separations area (movement of the shock wave location and of the flow separations levels away from the shock wave to the trailing edge).

The flow instabilities that induce buffeting are natural and self-sufficient. These phenomena can be observed on aircraft, rocket, turbomachine stages, etc.

The buffeting limits the flight envelope of civil aircraft. Even if buffeting is not dangerous and destructive, it can increase structural fatigue, affect aircraft maneuverability and decrease passengers comfort.

The aims of this study are to cancel out or decrease aerodynamic instabilities, "buffet", by using control systems. Only the "transonic buffet" type, with shock location and separated flows instabilities, is studied in this paper.

The "Vortex Generators" actuator situated upstream of the shock wave was used to decrease separated flows. A new moving part located at the trailing edge of the wing, "Trailing Edge Deflector" or TED, designed and patented by ONERA, was used to delay buffet and buffeting onset and to reduce buffet instabilities. It looks like an adjustable "Divergent Trailing Edge". It is also an active actuator, it can take different deflections or be driven by dynamic motions up to 250 Hz.

These control systems were tested in transonic flow cases. Aerodynamic studies on stiff 2D airfoils in ONERA T2 wind tunnel were performed to analyze the effect of the actuators on the instabilities. In a second phase, the new control system, TED, was studied in transonic three-dimensional flow. A model similar to transport aircraft was designed and manufactured with three independent TED and more than 100 unsteady pressure transducers. Tests were performed in ONERA S2 wind tunnel.

# 2. GENERAL DESCRIPTION OF THE TRANSONIC BUFFET PHENOMENON

Buffet can appear in many flight flow conditions. It is accentuated in transonic flow by the movement of the shock wave location caused by the flow separations, when they spread from the shock to the trailing edge. Only buffet in transonic flow with "shock wave / turbulent boundary layer interaction and flow separations", is described in this section.

In 3D transonic flow conditions, the shock wave / turbulent boundary layer interaction and flow separations induce flow instabilities, "buffet", and then structural vibrations on their eigen modes, "buffeting" (these modes can be different from the aerodynamic instability modes). It can have a significant effect on the aerodynamic behavior of the aircraft. The buffet phenomenon appears at high lift coefficients when the aircraft's Mach number or angle of attack increases. This phenomenon limits the aircraft's flight envelope (figure 1).

Data taken from the bibliography and performed 2D and 3D transonic flow tests have made it possible to describe the buffet phenomenon. Transonic flows are often crossed by shock waves induced by a sudden

recompression of the flow. These waves interfere with the boundary layer. A complex, localized interaction takes place with deterioration of local speed distribution until flow separation occurs [1, 2]. When the strength of the shock wave is strong enough, through an increase in the angle of attack or in the flow Mach number for example, the separated region spreads to the trailing edge, increases in size and thickens. Instabilities then develop on a large scale. The size of separation flow fluctuates as the location of the shock wave moves from downstream to upstream and *vice versa* (figure 2). The frequencies and amplitudes of the fluctuations depend on the shape of the airfoil and on the aerodynamic conditions of the flow. The pressure levels, and therefore the lift, vary very greatly. The term “buffet” can be used to describe these aerodynamics instabilities. It can produce “buffeting”.

Some aerodynamic differences have been observed between the 2D and 3D flow. They will be presented in next paragraphs.

# 3. DIFFERENT TYPES OF AERODYNAMIC ACTIONS – ACTUATORS CHOICE

The standard control systems increase the momentum of the low speed zones. They can be classified in two categories; those that have an effect on the boundary layer characteristics, and those that have a local impact on the shock/boundary layer interaction as the low speed zone decreases.

The effects of the following actuators were analyzed:

- the vortex generators (figure 3) located upstream of the shock wave location give energy to the boundary layer to stabilize it and so decrease the flow separations and the instability levels,
- the bump located at the shock location, decreases the intensity of the shock and thus reduces the shock wave/boundary layer interaction and may lower the flow separation levels [2,3].

A new actuator located at the airfoil trailing edge, the “Trailing Edge Deflector” (figure 4), is proposed due to its expected action on the aerodynamic field (shock wave location, flow separation, load distribution, etc), its efficiency for a broader range of flow conditions (Mach numbers, angles of attack) and a simple manufacturing. It is a new moving part on the wing.

In order to decrease and control the flow instabilities (e.g. shock location instabilities, pressure fluctuations, flow separations, etc.), it must be possible to move the actuators to different static positions and/or drive them with dynamic movements.

# 4. THE ACTUATORS UNDER TESTS

To try to decrease the flow separations, the buffet, the buffeting, two different types of actuators were chosen.

## 4.1 The Trailing Edge Deflector, “TED”

The “Trailing Edge Deflector” is located on the lower side of the trailing edge of a wing (figure 4). It is very small and its chordwise length is only 1 to 3 per cent of the airfoil chord. It can be moved to different static position and can take any deflection from 0° to 50°. The trailing edge thickness is increased and the airfoil flow is changed (figure 5). The 0° angular deflection corresponds to the original thickness of the airfoil trailing edge. TED looks like an adaptable divergent trailing edge. It can also be driven with dynamic movements up to 200 Hertz and ±10° of amplitude around a static deflection. An electrical motor is used to command the static positioning and the dynamic movements.

### 4.2 The Vortex Generators, “VG”

Following a study of the bibliography [4-6] and due to its expected action on the separated flow and therefore on buffet, a rectangular-shaped VG type was chosen. The dimensions were also chosen to simplify the manufacturing and the positioning on the model. The vortices are co-rotating with a VG angle of attack of 30°. The height is the local boundary layer height ($h=\delta$), the length is $L=5h$ and the spacing between each VG is $e=10h$. The VG location is at 33% of airfoil chord, 17% in front of the shock wave which is located at 50% the flow conditions with separated flow.

## 5. TWO DIMENSIONAL FLOW RESULTS

To begin with, these control systems were tested in a two-dimensional flow case [7-9]. Tests were carried out in the T2 wind tunnel of DMAE department in Toulouse [10]. The ONERA OAT15A airfoil was chosen. Its chord was 200mm length and it was equipped with 60 steady and 19 unsteady pressure transducers (figure 6). The boundary layer transition was fixed at x/c=7% on upper and lower sides of the model for all tests. The tests were performed at ambient temperature with a chord Reynolds number of 4.5 millions and free stream Mach number between 0.72 and 0.78. We focused on the aerodynamic instabilities and on the separated flow zones (buffet). The model structure was not subject to vibration. It was rigid and fixed to the test section walls.

Wall and wake pressure measurements have been essentially performed with the help of steady and unsteady transducers. The calculated precision was 0.1% for free flow conditions, for model pressure coefficients, local Mach numbers and aerodynamic coefficients. Tests repeatability have been shown a fidelity of measurements better than 0.05%.

### 5.1 Buffet onset

The buffet onset can easily be detected by means of the pressure fluctuation levels measured on the upper side of the model, at the shock location or between the shock and the trailing edge. Under buffet conditions, the measured signals are nearly periodical. A peak, characteristic of buffet in two-dimensional flow, is observed on the spectrum (figure 7). The frequency, around 80 Hertz for this airfoil, depended on the model’s chord and on the free stream flow conditions. The instantaneous location of the shock can be deduced from the pressure measurements provided by the very closely positioned transducers (precision better than 0.5% of the airfoil chord).

A sudden onset of buffet is observed due to the model’s angle of attack (figure 8). The angle of attack corresponding to the start of buffet is 2.85° without TED deflection The pressure fluctuation RMS are calculated not only in the 5-4000 Hertz frequency range but also in the 1000-4000 Hertz and 50-100 Hertz frequency ranges in order to determine the difference between the noise of separated flow instabilities and the buffet. The low frequency range is characteristic of oscillations of the shock location and of the separated flow levels (buffet). The high frequency range is characteristic of the separated flow noise. It increases before the buffet onset.

### 5.2. TED actuator effects

#### 5.2.1. Effect of a changing deflection of TED - Delay of the buffet onset

The experimental results show an improvement in the aerodynamic performances with the different static deflections of the Trailing Edge Deflector [7,8] (see also paragraph 6.3). An important effect is the delay of the buffet onset with the increase of the deflector angle (figure 9). With δ=0°, the buffet starts for Cl=0,97 and with δ=15°, it starts for Cl=1,04. This result is interesting and could represent a first control. But, is it possible to act directly on the instabilities?

### 5.2.2. Closed loop active control of buffet

The open loop tests have shown that, for deflector movement frequencies close to the buffet frequency, the deflector has a great influence in terms of frequency, amplitude and phase on the movement of the shock location and on separation flow level [7]. But, buffet could only be stabilized with a closed loop approach, based on the unsteady measurements of the distribution of static pressure on the airfoil section.

The control idea is to move the deflector against the natural movement of the shock location. When the shock location tends to go upstream, TED deflection is increased and *vice versa*. With the increase of the angle of attack for example, just at the onset of the buffet, the shock wave is at its downstream location and tends to go upstream. This represents the beginning of the shock location movement, the beginning of buffet. The TED deflection is increased to force the shock to move downstream and *vice versa*. The following relation directly calculates the signal given to the deflector by the control law from the unsteady measurements of the pressure transducers. These measurements give the aerodynamic fluctuations, separation flow levels, shock locations, etc.

$\delta(t) = \delta_m + \delta'(t)$ with $\delta'(t) = A \times (P(t-\tau))$

The control law and its parameters (A: gain, $\tau$: time delay, P: shock location) were determined empirically during the tests. With well-suited gain and time delay, the fluctuations of the shock location are clearly diminished (figure 10). Buffet is greatly reduced by the dynamic movement of the actuator driven by a closed loop active control with a well-defined law using the measurements of the model's unsteady static pressures.

A mathematical model of the described two dimensional buffet was founded and used to tests different control laws parameters and confirm the test chosen control laws [11].

## 5.3. "VG" actuator effects

The experimental results show the improvement in the aerodynamic performances on the polar (figure 11). It is effective for the highest lift coefficients but lowered the aerodynamic performances for the lower lift coefficients. An increase in the lift coefficients and a decrease in the drag coefficients can be observed for the separated flow conditions, ($\alpha$ greater than 2.9°). While the VG are situated upstream of the shock wave location, they produce a big effect on the separated flow zones. This can be seen in the wake measurements (figure 12). There is a decrease of the wake area. The separated flow zones are cancelled out by the VG.

The same remarks can be made concerning the pressure distribution on the airfoil (figure 13). For the separated flow conditions without VG in buffet conditions, the shock wave stays at its rearmost location with the VG corresponding to the shock location just before the onset of buffet. There is no shock location instabilities. The plotted pressure distributions are mean measurements. An inclined pressure distribution at the shock location indicates a movement of the shock.

The VG control decreases the separated flow zones and therefore the level of buffet. There is no buffet, no instabilities of the shock location. The pressure fluctuations, shock fluctuations and separated flow noise, are greatly reduced (figures 14 and 15). The selected frequency of the buffet phenomenon is cancelled out.

These VG actuators are static. They can be dynamic. They can be moved by means of mechanical systems or be replaced by air-jets. The VG device can be optimized. They can be used for the aerodynamic conditions of separated flow zones.

These results could also be used to show that buffet exists with separated zones and separated zones instabilities induce shock location instabilities.

# 6. THREE DIMENSIONAL FLOW RESULTS

## 6.1 Wind tunnel and 3D model

Tests were carried out in the S2Ma wind tunnel of ONERA's Modane center [12, 13]. "S2Ma" is a transonic or supersonic, pressurized closed circuit wind tunnel. The test section, equipped with top and bottom perforated walls, is 1,77m height, 1,75m width and 3,75m long. Calculations with 3D ONERA viscous-inviscid coupling were performed to help to design the model. In buffet onset conditions, the model was designed without separated flow at the root and the tip of the wing but with separated flow at the y/b deflectors' area. The model is equipped with three independent deflectors located between y/b=0,4 and 0,8. Its principal dimensions are 1,25 m spanwise and between 0,25 and 0,45 m chordwise (figure 16). With an existing experimental results analysis, these computations have also permitted the choice of the unsteady instrumentation location. The model is equipped with 6 accelerometers, 60 steady and 103 unsteady pressure transducers, and a 6 components wall balance. Each span sections (3) of unsteady static pressure was bringing into alignment with each deflector. The transducers are very close each other ($\Delta x/c$=2%) to calculate the shock wave location instabilities for buffeting conditions. Two potentiometers equip each deflector and give the mean and dynamic position. The model was manufactured by DERM department in ONERA Lille center. It is similar to the external wing of a civil transport aircraft. A simplified fuselage was added (figure 17). The boundary layer transition was fixed with carborundum grains at x/c=7% on upper and lower sides of the model for all tests. The tests were performed at ambient temperature with an aerodynamic mean chord Reynolds number of 8,3 millions and free stream Mach numbers between 0.80 and 0.84. The unsteady measurements were carried out simultaneously at a sampling rate of 5000 points per second and with a filtered signal of 2500 Hertz.

We will focus on the aerodynamic and structure instabilities (buffet and buffeting).

## 6.2 Buffet and Buffeting onset

Buffeting onset can be detected by accelerometer measurements and buffet onset by pressure fluctuations or shock location instabilities measurements. The buffeting onset (structural vibrations) with the angle of attack increase is also sudden (figure 18).

The measurements of unsteady static pressures can show the instabilities levels. With the increase of the angle of attack, the levels of separated flow instabilities increase. The shock location moves over 5% of chord on the external section(C) of the model (figure 19, 20). We can observe that the buffet onset appears at a slightly lower angle of attack than the buffeting onset, $\alpha$=3,15° for buffet onset and $\alpha$=3,35° for buffeting onset. We can consider that for this model and these transonic flow conditions, the shock location and separated flow instabilities, buffet, seem to be at the origin of the buffeting. But, in comparison with the 2D buffet phenomenon, the shock location is less moving for 3D buffeting.

With the help of visualisations and unsteady measurements, the general aerodynamics on the wing can be described. The first important observation is that, as in 2D flow, the buffet and buffeting onset appear when a separated zone spreads from shock to trailing edge. For this wing, the first separated flow zone spreading from shock to trailing edge appears between the central and external sections (B and C). But, in contrast with 2D flow, in such conditions and downstream the shock wave, the flow turns outwards (figure 21). The mean shock location does not stay at the same chord place versus the wing span. It goes upstream in the external section with the increase of the separated flow area.

At buffet onset, the shock location becomes to be unsteady in the external section (C), area where the separated flow spreads from shock to trailing edge. Then, with the angle of attack increase, the separated flow area becomes bigger and spreads to the internal wing direction. The shock location begins to move also in the central section (B). A big difference with the 2D flow buffet exists. There is not a selective

frequency of the shock location instabilities but a frequency band with higher energy (figure 22), 150 – 250 Hz for the external section. In span direction, the shock location instabilities in buffeting condition are not the same (figure 22). For $\alpha$=3,7° for example, there is no shock location instabilities in the internal section (A) and the frequencies of shock location instabilities are around 300-400 Hz for the central section (B) but with very low energy. In this section B, the shock location begins to move but has not enough energy to induce buffeting.

### 6.3 TED changing deflection - Delay of buffet and buffeting onset

As observed in 2D flow, the experimental results show the improvement in the aerodynamic performances on the polar with the different static positions of the Trailing Edge Deflector (figure 23). It is broadly efficient for the highest lift coefficient but lowers the aerodynamic performances by increasing the drag for the lower lift coefficients. It is therefore very important that it should be possible to move the deflector to different static deflections according to the lift coefficient.

An important effect is the delay in the onset of buffeting as the TED deflection is increased (figure 24). With $\delta$=0°, buffeting starts for Cl=0,65, with $\delta$=15°, it starts for Cl=0,69 and with $\delta$=30°, it starts for Cl=0,71. This result can be interesting because an aircraft flights at a lift coefficient dependent on its weight. The safety margin from buffeting would be kept with an increase of the aircraft lift.

### 6.4 Aerodynamic effects of a moved dynamic deflection of TED (open loop)

As in 2D flow tests, the deflectors can be driven by dynamic movements around a static deflection. There is a dynamic effect of the deflectors on the shock location but it is different from the 2D flow results. The natural buffet is not changed by the deflectors movements in open loop. But, in buffet conditions, there is a superposition of the deflectors influences and the natural buffet (figure 25). So the buffet and the buffeting can be increased by the deflectors motions for each tested frequencies. The deflectors dynamic movements change the shock location movements, they give supplementary movements of the shock location. The 2D control principle can be working but the 3D flow on the wing in buffeting conditions must be considered.

The buffeting level is also modified by the deflectors motions (figure 26). An increase of structural vibrations is observed, particularly for 230 Hz (torsion mode). This can confirm that aerodynamic instabilities (buffet) induce structural vibration (buffeting). The transfer function of the shock location/deflector motion can be determined by the open loop tests results. The deflector have no influence on the shock location for the highest frequencies (>250Hz) and have an important time delay.

### 6.5 Tests of closed loop active control attempts of buffet and buffeting

As in 2D flow, the idea is to move the deflector against the natural movement of the shock location. When the shock location wants to go upstream, the deflector angle is increased and *vice versa* (figure 5). The control principle is the same. Some attempts of closed loop active control with a different control law for each section have been tested but without success. Just a little modification of the shock location spectrum and level vibration have been observed.

The 3D flow observed on the wing is very different from the 2D flow on the airfoil. An other difference with 2D flow results is that the deflectors are not placed in the same way. Due to separations, the principal flow direction downstream the shock is not in the deflectors and the unsteady transducers axis (figure 21).

### 6.6 Simulations of buffet and buffeting closed loop active control

Simulations of control based on tests measurements and on the transfer function of shock location/deflector motion have be done. The shock location instabilities are greatly reduced by the deflectors (figure 27a). But, we can observe that a lot of energy is needed (figure 27b). This high energy is necessary only to control the highest measured frequencies. But to control buffet (f<250Hz) and then buffeting, it is not necessary to control these highest frequencies. The signal can be filtered but this gives more time delay and the closed loop control becomes more difficult.

Research investigations have been done on signal treatment to create a new signal similar to the measured one but with reduced spectrum (f<250hz). The sampling rate, "acq", was changed from the original signals of the pressure transducers and the shock position, acq=2048 Hz, to a new built signal, acq=500 Hz (figure 28). The test case was chosen with established buffeting and with buffet (shock location instabilities) only on the external section ($\alpha$=3,7°). On this wing, the instabilities first appeared on the external area and the buffet must be controlled at the beginning before it becomes too much important. In open loop, a big influence of the central TED on buffet of the external section was shown (figure 29). This is certainly due to the transversal flow downstream the shock location described on figure 21 and on the pressure perturbations direction (figure 30).

With the new signal treated from the original one and the transfer functions of the effect of the central deflector on the external shock location, closed loop controls were attempted with the 2D control principle. The shock location instabilities, buffet, are greatly reduced (figure 31). The needed amplitudes of the deflector motion are not important (figure 32), less than 20°. The buffet and certainly the buffeting were reduced by TED with an active control. But the effect of the central deflector on the central section of the wing must be also considered. The control law will be more complicated because combinations of all sections measurements and all deflectors motions would be used.

The flow described on the studied model had shown that the buffet, the shock position instabilities, that induced buffeting, appeared on the external area of the wing. In addition, the flow downstream the shock location was greatly oriented to the external wing in buffet conditions. This important three dimensional flow had given more difficulties to control these instabilities by TED in comparison of the studied two dimensional flow. But, this type of control could be more easier on a transonic wing of a transport civil aircraft because the flow is less oriented to the external wing and the separated flow, than the shock location instabilities can appeared first at the central area of the wing.

## 7. CONCLUSIONS

This study has given some physical observations on the buffet phenomenon with shock; movement of the shock location, unsteady levels of separated flows, frequencies of the phenomenon dependant on the free stream flow conditions, model dimension and configuration, etc. A bibliography study was performed to help to the choice of the type of aerodynamic action to control the buffet and the separated flow zones. The following actuators were used, "Vortex Generators" situated upstream of the shock location and a new moving part designed by ONERA and situated at the trailing edge of the wing, "Trailing Edge Deflector" or TED. Models with significant unsteady instrumentation were manufactured, 2D and 3D flow tests were performed.

The VG control decreases the separated flow zones and so the buffet level. With control, there is no buffet, no instabilities of the shock location. The pressure fluctuations, shock fluctuations and separated flow noise, are greatly reduced. The selected frequency of the buffet phenomenon is cancelled. With the separated flow decrease, the airfoil aerodynamic performances are increased. It is not necessary to propose a very precise position of the VG. They must be situated upstream the separated flow zone, upstream the shock location.

For 2D and 3D flow, selected static positions of TED actuator increase the aerodynamic performances and delay the buffet onset. It has the same effect as a divergent trailing edge but it can be moved. Its action can be optimized. It can be used when necessary. It can also change the rear load of the airfoil and the load distribution on the wing can be adapted to flow conditions. That can be an interesting effect for wing equipped with some TED devices. TED acts also on the shock location. It can control the buffet with shock location instabilities with a closed loop control law using unsteady measurements. This control in 3D flow is more difficult but may be possible.

The VG are simpler to use but they decrease the aerodynamic performances when there is no separated flow. These used VG actuators were fixed. But, they could be moved by mechanical systems or be replaced by air-jets. The VG device should be optimized. They could be used when necessary. Their efficiency on separated flow and on buffet, buffeting for 3D flow seems to be sure. But, tests investigations must be done in buffeting conditions.

The VG seems to be the simplest actuator to use. TED actuator delays the buffet and the buffeting onset but would need more complicated closed loop laws for dynamic control in 3D flow. But according to the aerodynamic conditions, these actuators can be complementary and be active when necessary. VG can act on separations and TED on load distribution and shock location.

## ACKNOWLEDGMENTS

This paper presents the VG results from studies which have been supported by the French government agency, DGAC, and which have been carried out in collaboration with Dassault Aviation company and ONERA. The TED actuator results comes from studies of the ONERA Research Federator Project “Buffet Flow Control”, collaboration between different ONERA departments, DAAP, DCSD, DERM, DMAE, DPRS and DSNA.

## REFERENCES

[1] J. Délery - L’interaction onde de choc/couche limite turbulente et son contrôle. (réunion AGARD/FDP, Bruxelles, 21-23 mai 1984 – T.P. no 1984-27)

[2] R. Bur, B. Corbel, J. Délery, D. Soulevant - Transonic shock wave/boundary layer interaction control. Complementary experiments on suction slot and bump control. ONERA contribution to Task 1 of the Euroshock 2 project. RT 131/7078 DAFE/Y – January 2000.

[3] H. Sobieczky, W. Geissler, M. Hannemann - Expension shoulder bump for wing section viscous/wave drag control. Contribution at “FLOWCON” – IUTAM Symposium on Mechanics of Passive and Active Flow Control, September 1998.

[4] J.C. Lin, G.V. Selby, F.G. Howard - Exploratory study of Vortex-generating Devices for turbulent Flow Separation Control – AIAA 91-0042 – 29th Aerospace Sciences Meeting – January 7-10, 1991/Reno, NV

[5] T.J. Barber, J.S. Mounts, D.C. McCormick - Boundary Layer Energization by Means of Optimized Vortex Generators. – AIAA 93-0445 – 31st Aerospace Sciences Meeting & Exhibit – January 11-14, 1993 / Reno, NV

[6] J.C. Lin - Control of Turbulent Boundary Layer Separation using Micro-Vortex Generators. – AIAA 99-3404 – 30th AIAA Fluid Dynamics Conference – 26 June – 1 July, 1999 Norfolk, VA

[7] D. Caruana, M. Corrège, O. Reberga, C. Despré, A. Mignosi - Buffet and Buffeting Active Control. – AIAA 2000-2609 – Fluids 2000 – 19-22 June 2000 / Denver, CO.

[8] C. Despré, D. Caruana, A. Mignosi, O. Reberga, M. Corrège, H. Gassot, J.C. Leballeur, P. Girodroux-Lavigne - Buffet Active Control – Experimental and numerical results. – Symposium R.T.O. – Active Control Technology for Enhanced Performance Operational Capabilities of Aircraft – Braunschweig/Germany – May 2000.

[9] O. Reberga - Etude expérimentale et numérique du phénomène de tremblement sur profil d'aile et de son contrôle en écoulement transsonique avec onde de choc. Phd Thesis ENSAE – Juin 2000 – Toulouse.

[10] A. Séraudie – J.P. Archambaud - The Cryogenic Induction Tunnel T2 at Toulouse. (AGARD FDP/VKI Special Course – May 1996).

[11] A. Le Pourhiet, M. Corrège, D. Caruana - Mathematical modelling and active control of oscillators. Application to buffet and to compressor surge. (ICAS, Toronto - Canada, September. 2002)

[12] D. Caruana, C. Despré, A. Mignosi, M. Corrège, A. Le Pourhiet – Buffet and buffeting Active Control with a Flap Actuator. – ICIASF 2001 – August 27, 30 2001 – Cleveland, Ohio, USA.

[13] Despré - Etude expérimentale et numérique du phénomène de tremblement et de son contrôle en écoulement transsonique bi et tri-dimensionnel. Phd Thesis ENSAE – Octobre 2001 - Toulouse.

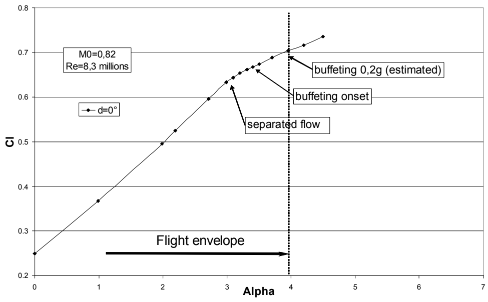



**Figure 1 – Example of flight envelope limitation.**

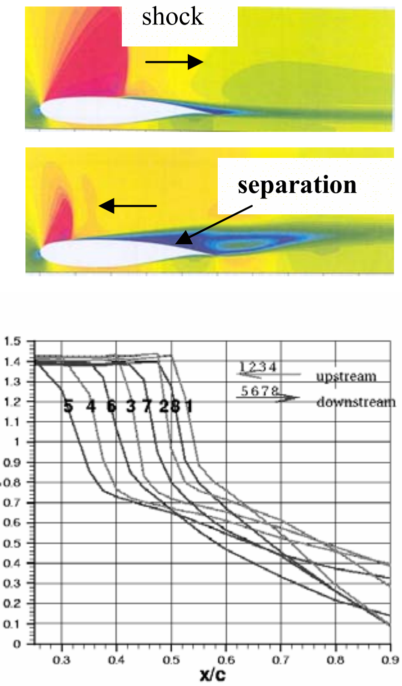



**Figure 2 – Shock position and separated flow level instabilities.**

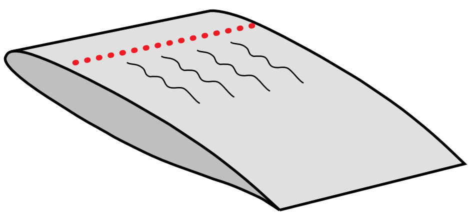


**Figure 3 – Vortex generators.**

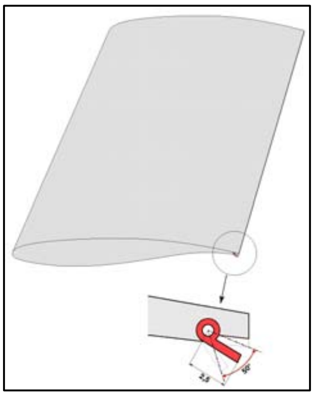


Figure 4 – Trailing edge deflector.

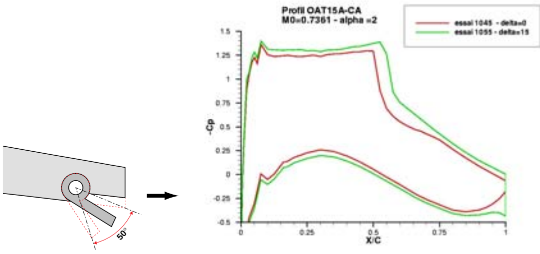



Figure 5 – Airfoil flow modification by different positions of the Trailing Edge Deflector (0° and 15°).

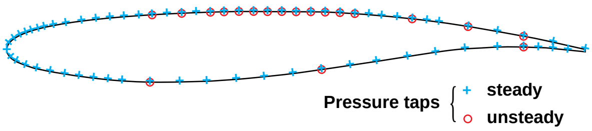



Figure 6 – OAT15A model instrumentation.

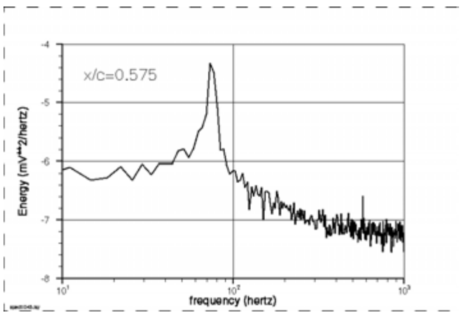



Figure 7 – shock position spectrum.

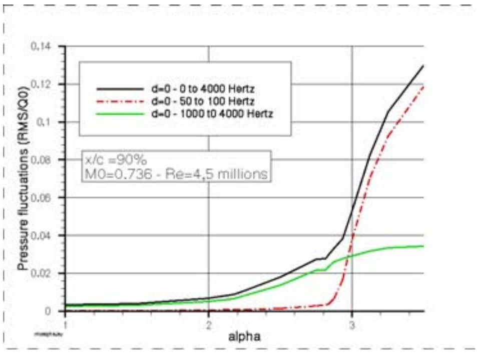



**Figure 8 – Buffet onset.**

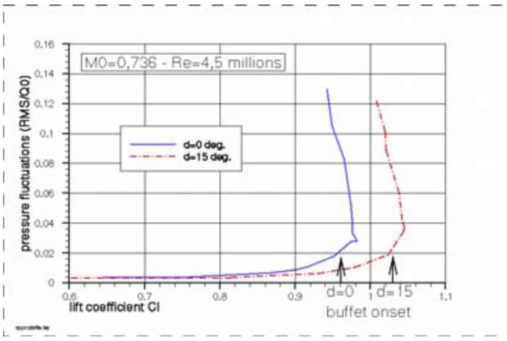



**Figure 9 –Delay of the buffet onset with the increase of TED deflection.**

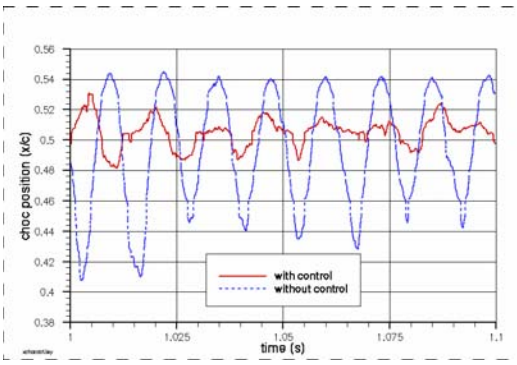



**Figure 10 – 2D closed loop control with TED.**

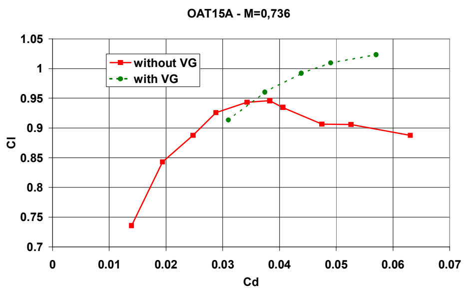



**Figure 11 – VG effect on polar.**

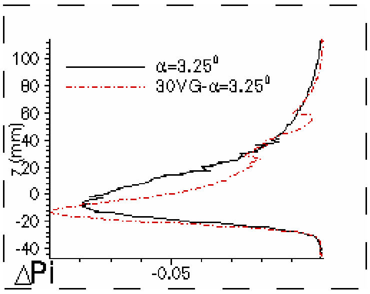



Figure 12 – VG effect on wake – α=3,25°.

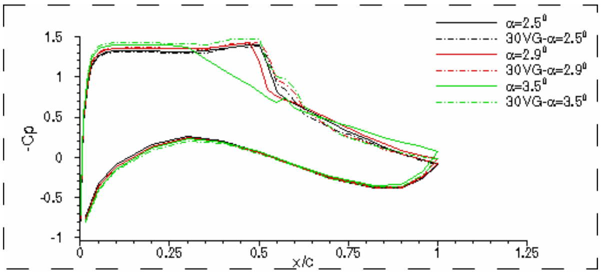



Figure 13 – VG effect on pressure distribution.

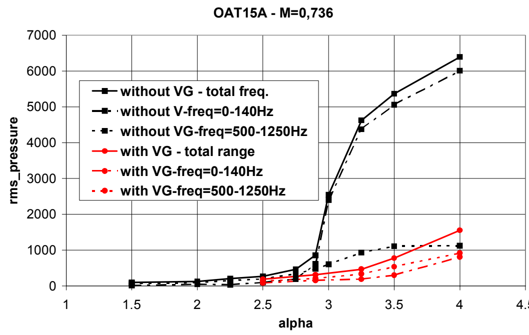



Figure 14 – VG effect on separated flow and buffet.

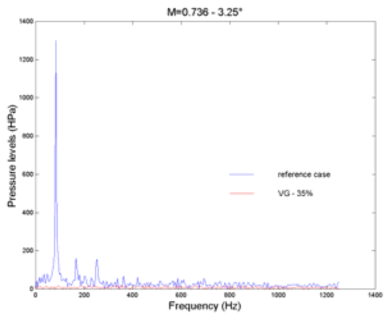



Figure 15 – VG control of separations and buffet.

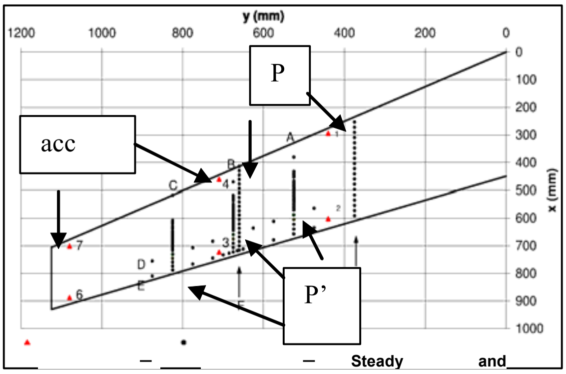



Figure 16 – Accelerometers (Acc) and static pressure transducers (steady=P, unsteady=P').

Figure 17 – 3D model in S2 wind tunnel.

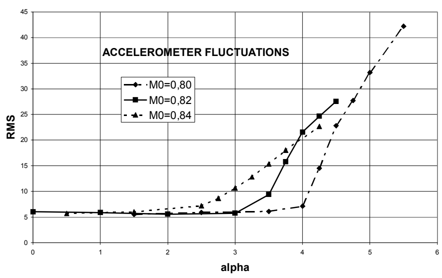



Figure 18 – Buffeting onset for each tested flow Mach number.

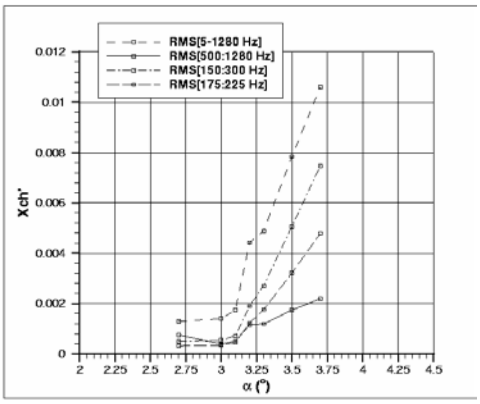



Figure 19 –Buffet onset – External section – M0=0,82.

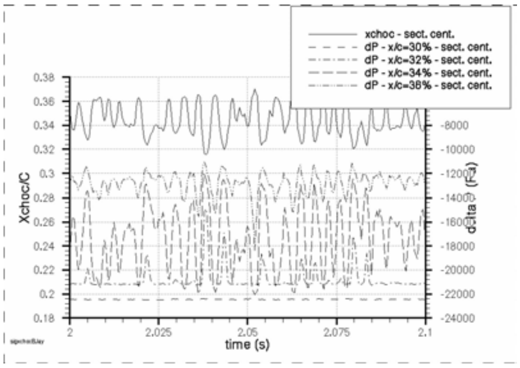



**Figure 20 – Shock position instabilities.**
**M0=0,82 - $\alpha$=3,7°.**

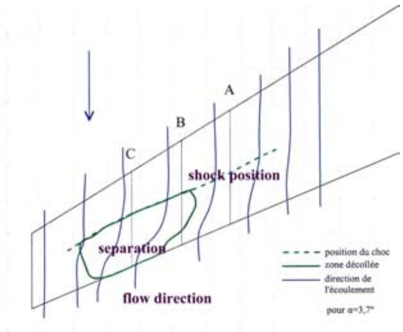



**Figure 21 – Separated flow areas evolutions.**
**M0=0,82 - $\alpha$ = 3.7.**

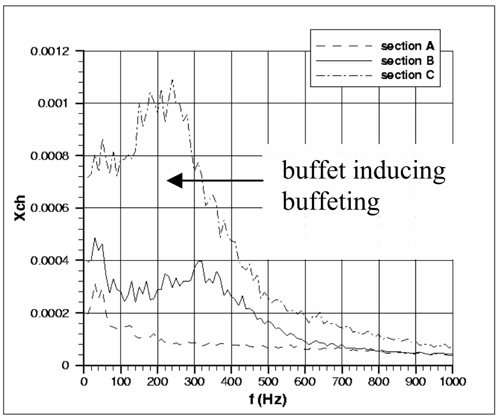



**Figure 22 –Spectrum of the shock position instabilities.**
**M0=0,82 - $\alpha$=3,7°.**

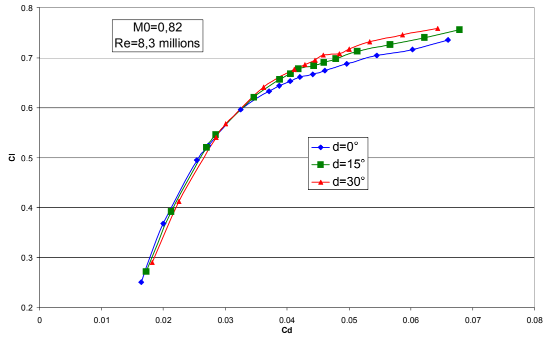



**Figure 23 – Effect of a changing deflection of TED on aerodynamic polar – 3D flow – M0=0,82.**

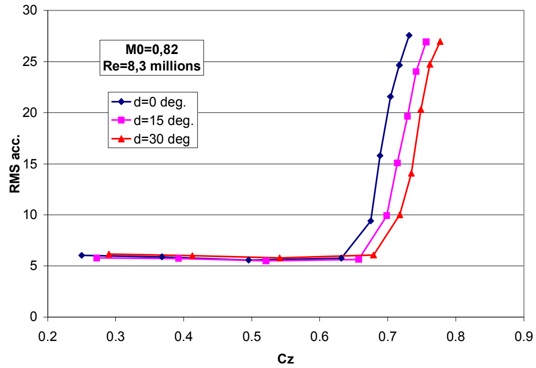



**Figure 24 –Delay of the buffeting onset with the increase of the TED deflection – 3D flow – M0=0,82.**

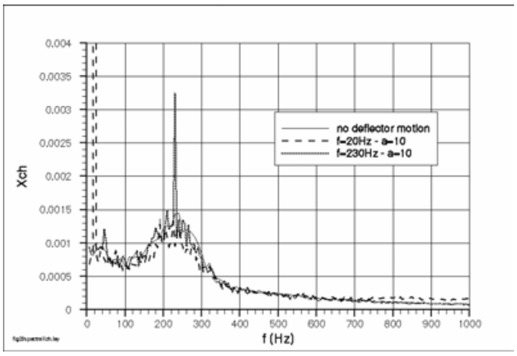



**Figure 25 –Open loop - Shock position spectrum. Central section - 3D flow – M0=0,82.**

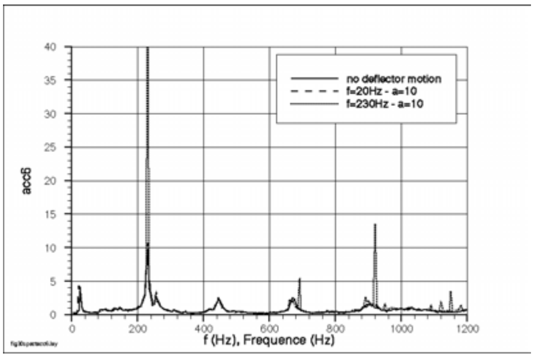
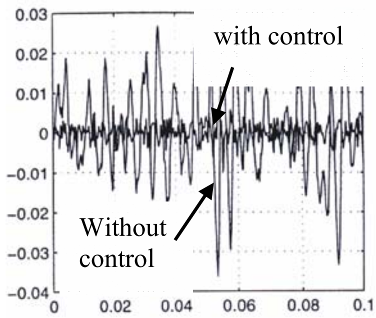
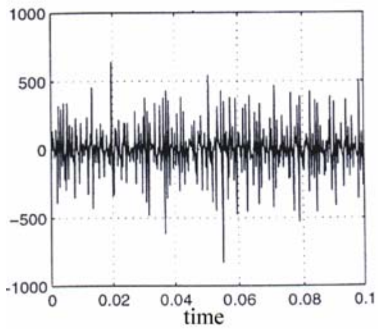



**Figure 26 –Open loop – Model vibrations.
Accelerometer measurements - 3D flow – M0=0,82.**




**a) Shock position with and without control.**




**b) Deflector motion.**

**Figure 27 – Buffet control simulation based on tests measurements and shock/deflector transfer function.**

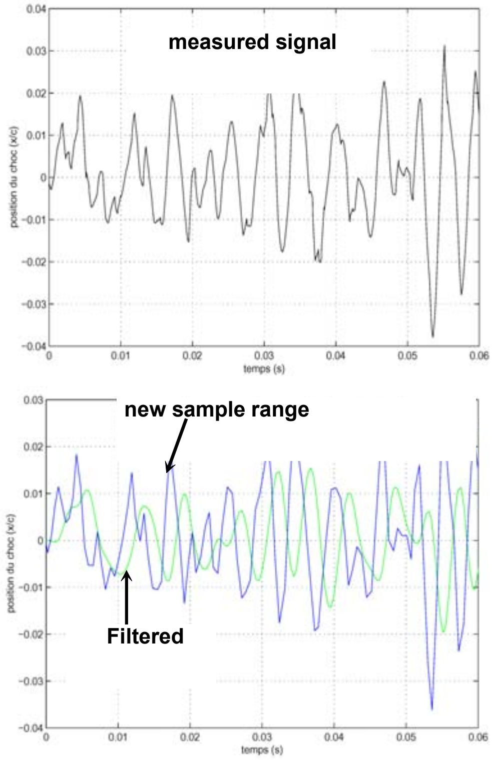



**Figure 28 – New built signal with 500Hz of sample range.**

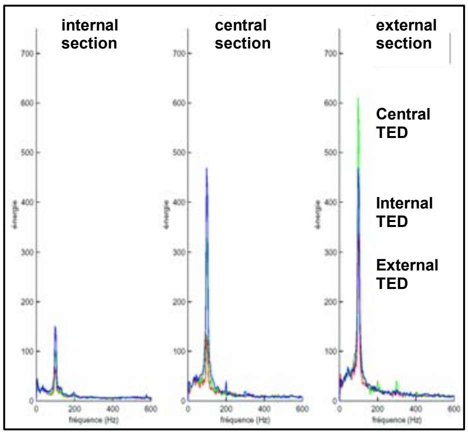



**Figure 29 –Effect of sinusoidal movements of each TED on the shock position of each wing section.**

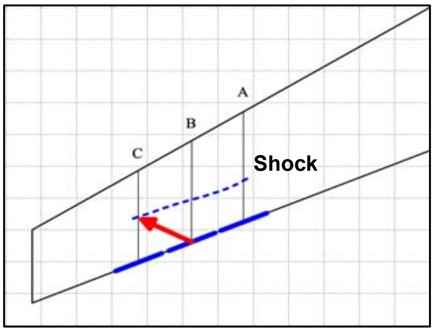



**Figure 30 – Pressure perturbations direction by TED.**

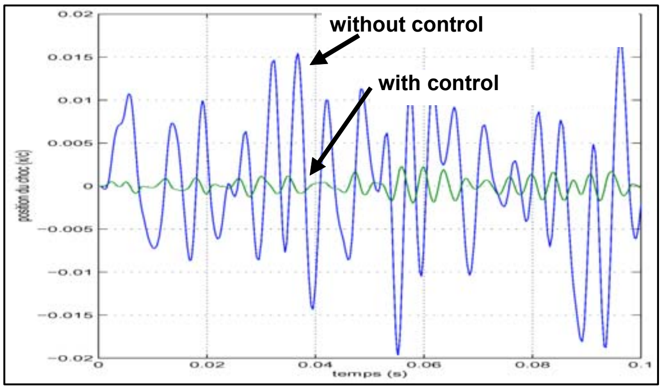



**Figure 31 – Buffet control on the wing external section by the central TED – Shock position signal.**

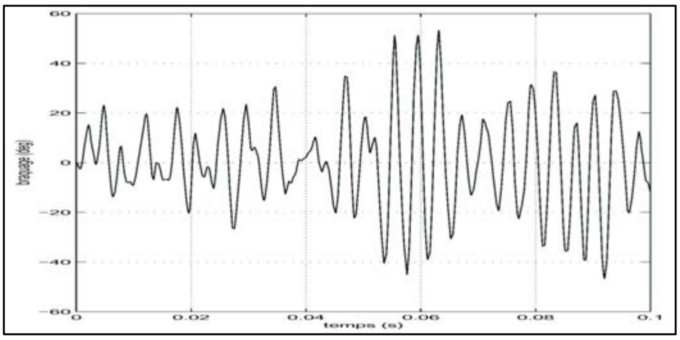



**Figure 32 – Signal of the central TED motion during closed loop control.**